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INVESTIGATION OF LAUNCHING A PARTICLE WITH A MACH STEM DETONATION

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19. ABSTRACT (CONTINUE ON REVERSE IF NECESSARY AND IDENTIFY BY BLOCK NUMBER)

The ability of a Mach stem detonation to produce enhanced flyer kinetic energy compared to regular detonation of a geometrically equivalent charge is investigated. The charge configuration was chosen to utilize the observation that the pressure and velocity produced by the Mach stem detonation match conditions for a steady shock wave in aluminum. Computer simulations are presented to show the effect of this matching of the detonation to the metal.

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INTRODUCTION

Previous work by members of the Initiation and Detonation Group (refs 1 and 2) investigated the detonation of charges consisting of two cylindrical shells of explosives arranged to form a "Mach stem" detonation. This detonation wave moved at the velocity of the outer (faster) layer of explosive, but produced a finite core region of very high pressure (much greater than these explosives can usually yield). Details can be found in the references. An interesting feature of these detonations is that the core pressure is high enough for these waves to match the pressure-velocity characteristics for pure shock waves in some metals (fig. 1). Because the shock pressures and shock velocities match, there is the possibility of producing an essentially one-dimensional shock wave in a metal rod by embedding the rod in the explosive core. Without the Mach stem effect, the shock induced into such a rod would be dominated by two-dimensional effects.

The particle velocity produced in the rod by such a shock is fairly slow (around 2.3 km/s for aluminum) and is strongly affected by the expansions which enter from the ends of the rod. However, it seems plausible that a significant translational velocity can be imparted to the rod, if it is kept short enough. Some computer simulations were carried out to examine this phenomena.

COMPUTER SIMULATION

As can be seen from figure 1, the PBX 9501/TNT system matches with a shock in aluminum fairly well. This system (substituting PBX 9404 for the PBX 9501) was chosen as a base line. Dyna2D was used for the calculations because of its user-friendly rezone capabilities. A major convenience of using Dyna was that it was being routinely used by members of the staff, so expert advice was available when needed. Charge initiation was assumed to occur simultaneously along z=0 (which was taken as a stonewall in the calculation). A significant distance is required for the center of the Mach stem detonation to obtain the nominally correct, overdriven detonation pressure as predicted by the Tiger code. Buildup of centerline pressure in the TNT is complete at 4.3 cm (1.35 charge radii) from the initiation plane. The length of the charge assumed in the calculation was chosen just slightly longer than this value (5 cm) so full pressure was obtained before the detonation impacted the rod. Charge radii were chosen to match dimensions being used in laboratory studies.

Comparison calculations were done assuming the charge consisted of all PBX 9404 (no Mach stem effect). These also required the same runup distance to reach a (nominally) steady pressure corresponding to the correct detonation pressure.

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A typical grid is shown in figure 2 Most calculations assumed a rod of 0.7 cn ngth; however, a calculation with a 1.4 cm aluminum rod was made to show how erformance falls off as length increases. The launching of the rod depends on main.aining a significant pressure on its rear face until the expansion from the front surface arrives at the rear; therefore, there are limits on rod length. Near the front of the rod, sufficient radial velocity is induced to cause jetting of rod material. The tip acquires high velocity, but the calculation cannot follow events in this region very well. Frequently, the tip cells had to be dropped from the calculation in order to continue.

A list of calculations is given in the table. None of these calculations proceeded smoothly, so the results probably should be considered as tentative. The difference between an aluminum rod, where the shock matches with the Mach stem conditions, and a copper rod, which does not match, is shown in figures 3 through 8. Gradients are much smoother in the aluminum, and the axial velocity is fairly uniform across the rod. The copper has a wildly varying axial velocity due to the shock having converged on the axis.

The calculated average axial velocities are shown in figure 9. These represent the total axial momentum divided by the total mass. Lost tip cells are not included in the momentum. The "Gurney" lines are for a sandwich geometry with infinite tamper mass having the same charge-to-mass ratio as the rods. They represent an upper limit to velocity if there are no radial losses. The 0.36 cm radius aluminum rod achieves a velocity close to the idealized Gurney value. When the layered explosive charge is replaced by solid PBX 9404, the velocity drops as shown. Only 0.18 cm radius copper rods were tried. Distortion was more severe than for the aluminum, and the calculations stopped (from numerical difficulties) at earlier times. The layered charge improves the copper average velocity also, even though there is no matching effect for copper. A single calculation for a 1.4 cm long rod is indicated. Its velocity was the same as the shorter rod launched by solid PBX 9404. Velocity of the rear of this rod had nearly slowed to zero before the expansion from the front reached it; this rod is clearly too long for this particular charge.

Lastly, a velocity obtained from a copper flyer plate experiment is shown in figure 10. It has a slightly higher velocity than calculated for the copper rods. By contrast, when the sandwich Gurney formula is applied to the experimental charge-to-mass ratio, the predicted velocity is 145% greater than measured. This difference is due to the great radial losses inherent in the experiment. The effect of radial losses would presumably affect aluminum flyer plates in a similar fashion, causing the much higher velocity of the aluminum rod to stand out more dramatically.

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The aluminum rods ended up having a large velocity gradient along their length. Thus, their kinetic energy is larger than if the entire rod were moving at the average velocity. The total kinetic energy is shown in figure 11. At 0.36 cm radius, the rod has virtually the same kinetic energy as would be calculated for a plate of equivalent mass using the sandwich Gurney formula (without any losses). Without the Mach stem effect, the total kinetic energy is down by 50%.

All the rods formed a sort of jet. The configuration for the 0.18 cm aluminum rods are shown in figures 12 and 13, with the corresponding density contours in figure 14 and 15. The jet produced by the Mach stem is smoother and has higher tip velocities. The tip region in the solid PBX 9404 calculation has low density, which probably indicates only debris have the high velocity. The Mach stem jet seems to have a hollow along the axis, which separates regions of (nominally) different axial velocity; one with velocities from 6.9 to 7.9 km/s and a larger one with velocities 2.9 to 4.4 km/s. Both regions are stretching. The solid PBX 9404 calculation shows a large region with a velocity of 2.8 km/s with the nose being stretched up to 4.9 km/s and somewhat faster debris ahead.

The copper rod with Mach stem has low velocity debris at the rear as well as fast debris in front. There is a solid region with velocity gradient from 1.4 to 3.1 km/s. The copper rod launched by solid PBX 9404 does not show much velocity gradient, with most contiguous material having velocity from 0.92 to 1.4 km/s and a smaller amount of high velocity debris ahead.

CONCLUSION

Computer simulations show that arranging explosives so the detonation forms a Mach disk can be used to improve efficiency of energy transfer to flyers vis-a-vis the same configuration using a uniform charge. Also, matching the pressure and detonation properties to the shock properties of the flyer material can yield smoother, more uniform conditions in the flyer. However, the configuration considered here always leads to stretching of the flyer in flight. Further, a large amount of explosive is required to allow for buildup of the detonation, and the rod has to be kept short so pressure at the rear does not have time to vanish before the expansion from the front of the rod arrives. Efforts to launch longer rods would need to reduce both of these adverse phenomena.

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Table 1. Calculations

| Rod radius	Rod length	Charge system	Rod material	Figure 9 symbol
0.18	0.7	PBX9404/TNT	Aluminum	Rod/Mach stem
0.18	0.7	Pure PBX9404	Aluminum	Rod/PBX9404
0.18	0.7	PBX9404/TNT	Copper	Rod/Mach stem
0.18	0.7	Pure PBX9404	Copper	Rod/PBX9404
0.36	0.7	PBX9404/TNT	Aluminum	Rod/Mach stem
0.36	0.7	Pure PBX9404	Aluminum	Rod/PBX9404
0.72	0.7	PBX9404/TNT	Aluminum	Rod/Mach stem
0.72	0.7	Pure PBX9404	Aluminum	Rod/PBX9404
0.18	1.4	PBX9404/TNT	Aluminum	Long rod/Mach stem
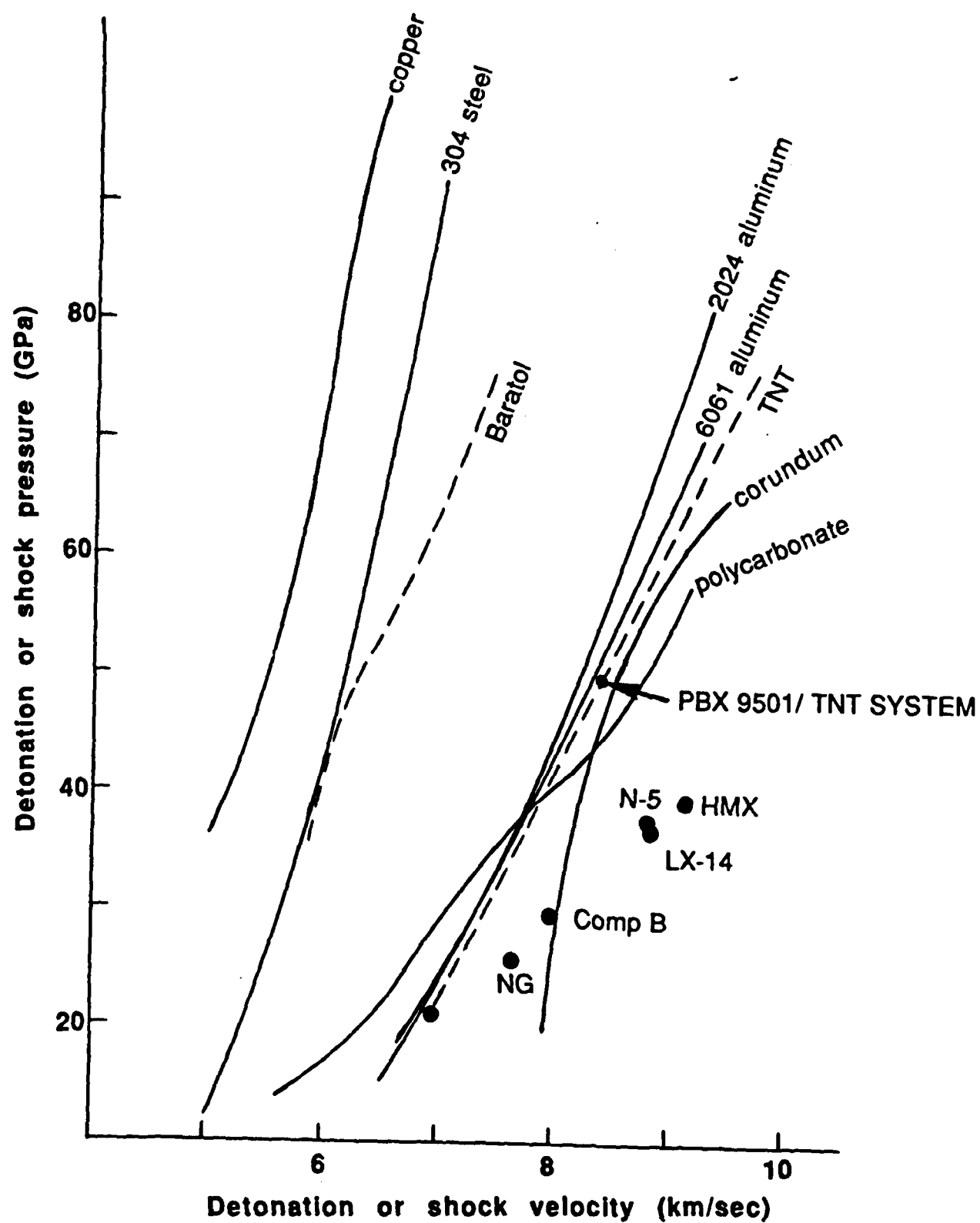
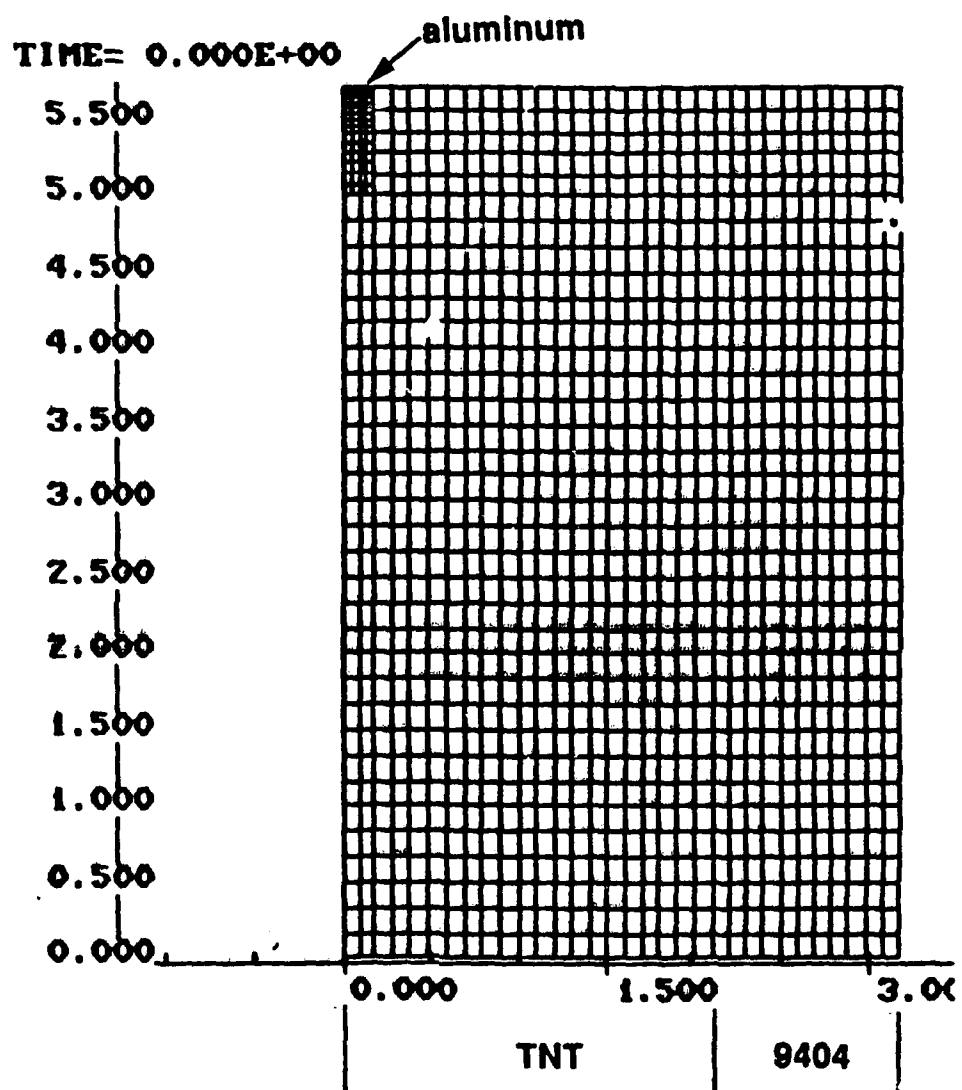Figure 1. Matching of detonation characteristics to shock characteristics

Figure 2. Typical grid

MACH STEM DETONATION
TIME=   0.79870E CONTOURS OF PRESSURE
DSF =   0.10000E+01

MIN(-)= 8.99
MAX(+)= 8.31
CONTOUR LEV

A= 0.61E-
B= 0.17E+
C= 0.18E+
D= 0.24E+
E= 0.30E+
F= 0.37E+
G= 0.43E+
H= 0.49E+
I= 0.55E+

mbar

Figure 3. Pressure for a 0.18 cm aluminum rod in a Mach stem at 8 µs

MACH STEM DETONATION CONTOURS OF PRESSURE

TIME=   0.82401E
DSF =   0.10000E+01

MIN(-)=-0.51
MAX(+)= 0.66
CONTOUR LEV

A= 0.66E-
B= 0.13E+
C= 0.20E+
D= 0.26E+
E= 0.33E+
F= 0.40E+
G= 0.46E+
H= 0.53E+
I= 0.60E+

mbar

5.900E+00
5.800E+00
5.700E+00
5.600E+00
5.500E+00
5.400E+00
5.300E+00
5.200E+00
5.100E+00
5.000E+00
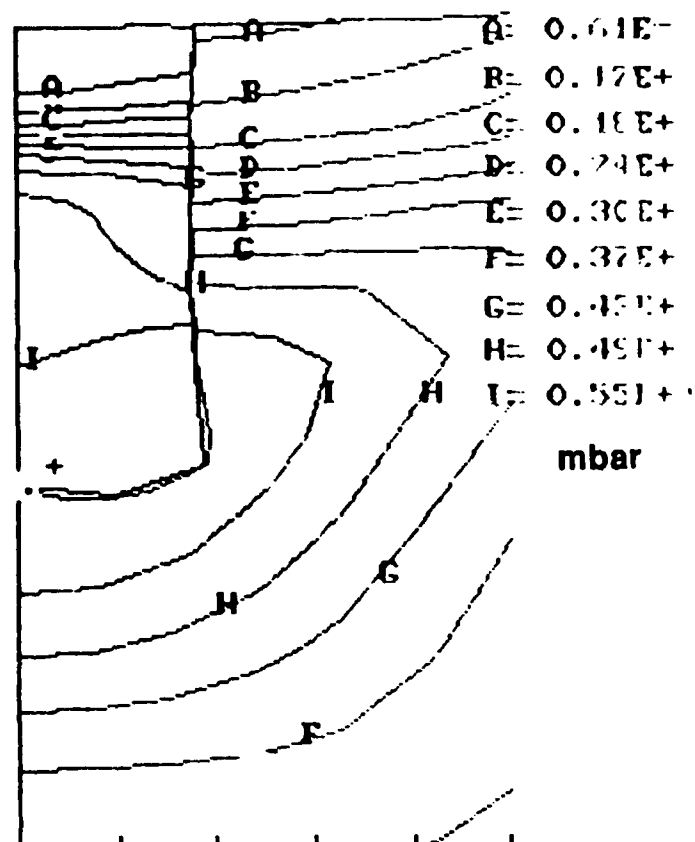4.900E+00

-5.000E-01   -2.000E-01   1.000E-01   4.000E-01
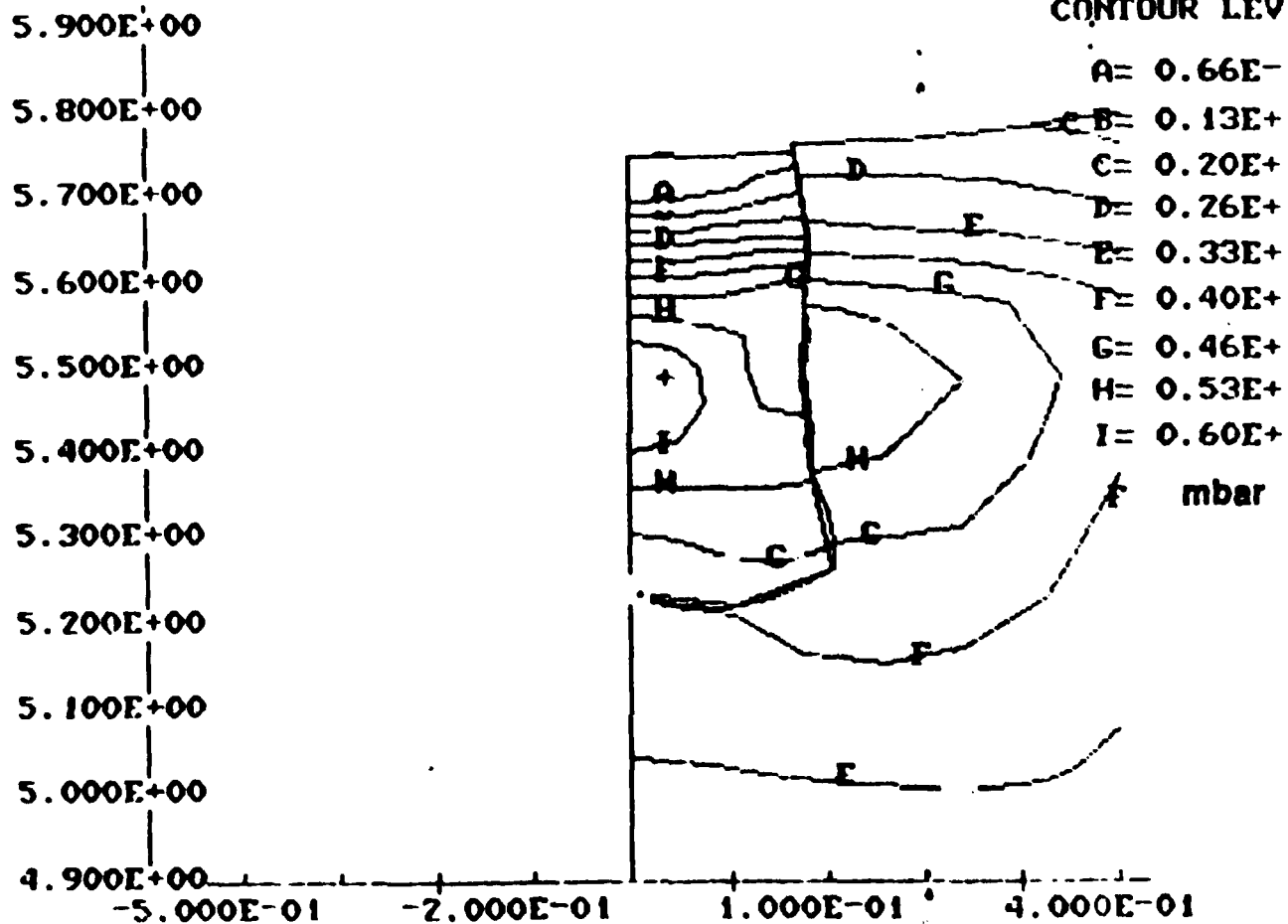
Figure 4. Pressure for a 0.18 cm aluminum rod in a Mach stem at 8.24 µs

MACH STEM DETONATION
TIME=   0.82401E CONTOURS OF AXIAL VELOCITY
DSF =   0.10000E+01

MIN(-)= 8.31
MAX(+)= 8.41
CONTOUR LEV

5.750E+00

5.700E+00

5.650E+00

5.600E+00

5.550E+00

5.500E+00

5.450E+00

5.400E+00

5.350E+00

5.300E+00

5.250E+00

5.200E+00

5.150E+00

-3.000E-01   -1.500E-01   0.000E+00   1.500E-01   3.000E-0

A= 0.23E+
B= 0.25E+
C= 0.27E+
D= 0.29E+
E= 0.31E+
F= 0.33E+
G= 0.35E+
H= 0.37E+
I= 0.39E+

cm/μsec
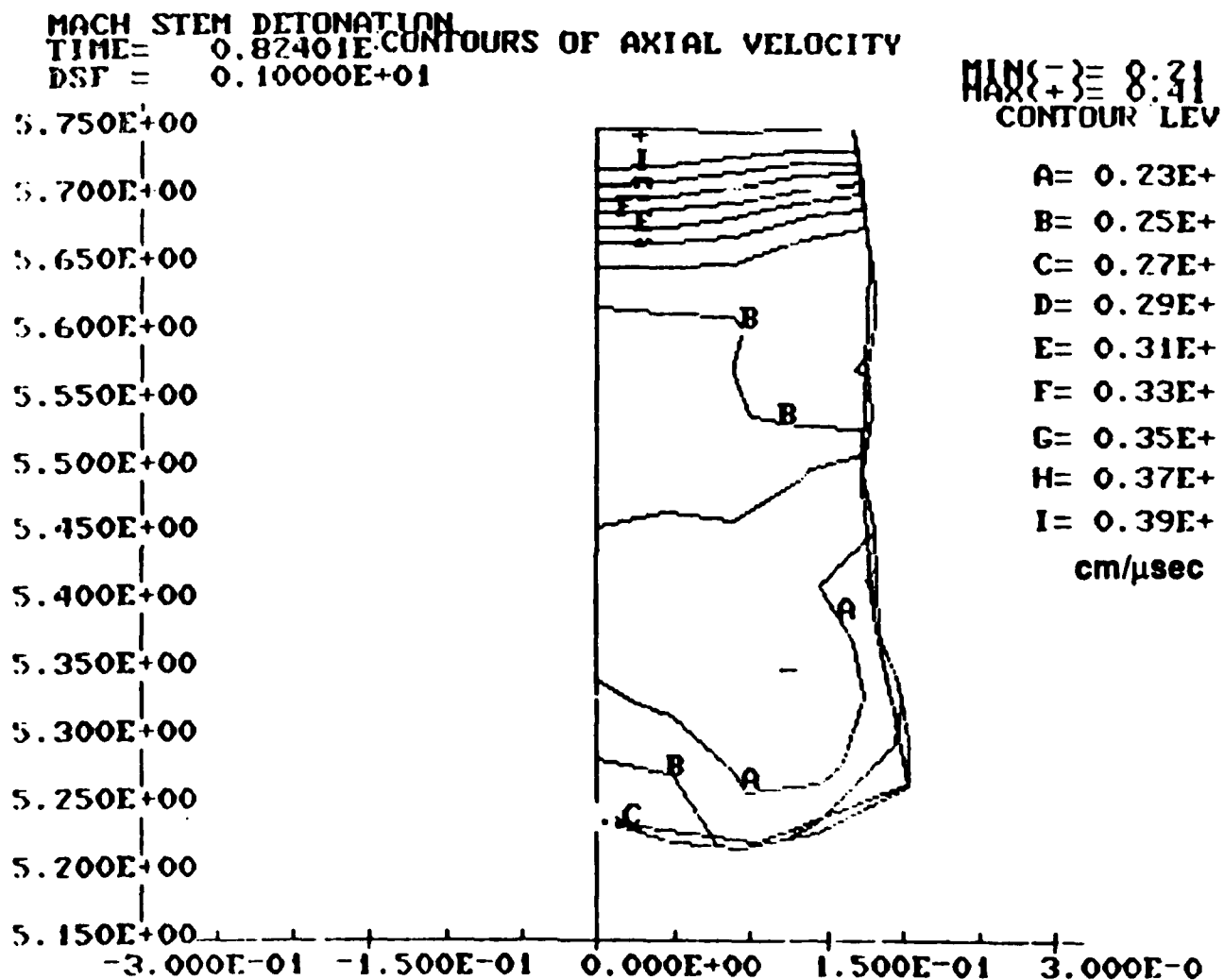
Figure 5. Axial velocity for a 0.18 cm aluminum rod in a Mach stem

MACH STEM DETONATION
CONTOURS OF PRESSURE
TIME=   0.79857E
DSF =   0.10000E+01

MIN(-)= 0.00
MAX(+)= 0.91
CONTOUR LEV

A= 0.91E-
B= 0.18E+
C= 0.27E+
D= 0.36E+
E= 0.46E+
F= 0.55E+
G= 0.64E+
H= 0.73E+
I= 0.82E+

mbar

5.700E+00
5.600E+00
5.500E+00
5.400E+00
5.300E+00
5.200E+00
5.100E+00
5.000E+00
4.900E+00
4.800E+00

-5.000E-01   -2.000E-01   1.000E-01   4.000E-01
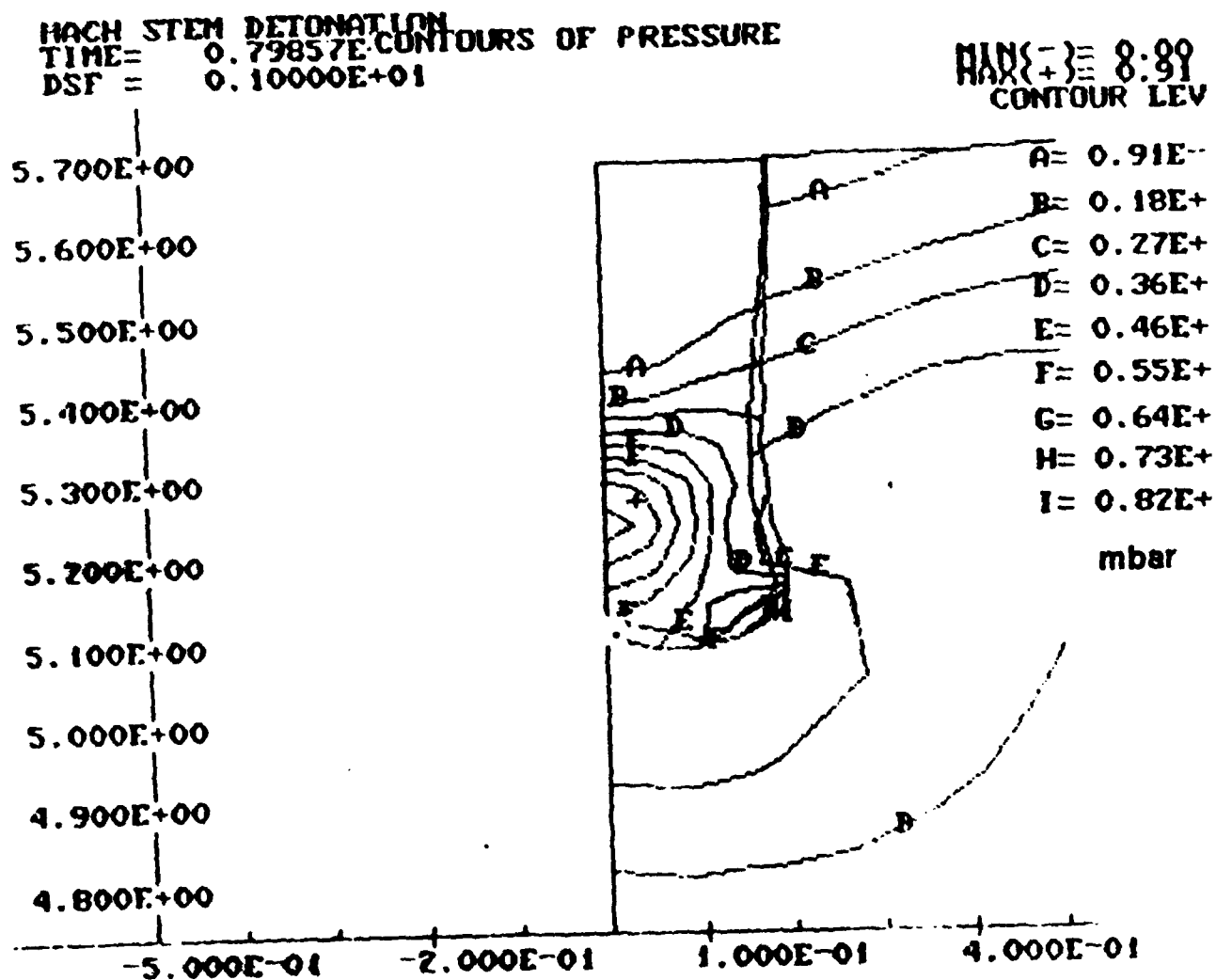
Figure 6. Pressure for a 0.18 copper rod in a Mach stem at 8 μs

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MACH STEM DETONATION
TIME=   0.82424E-CONTOURS OF PRESSURE
DSF =   0.10000E+01

MIN(-)= 0.17
MAX(+)= 0.13
CONTOUR LEV

5.900E+00

5.800E+00

5.700E+00

5.600E+00

5.500E+00

5.400E+00

5.300E+00

5.200E+00

5.100E+00

5.000E+00

4.900E+00

5.000E-01   -2.000E-01   1.000E-01   4.000E-01

A= 0.14E+
B= 0.27E+
C= 0.40E+
D= 0.53E+
E= 0.66E+
F= 0.78E+
G= 0.91E+
H= 0.10E+
I= 0.12E+

mbar
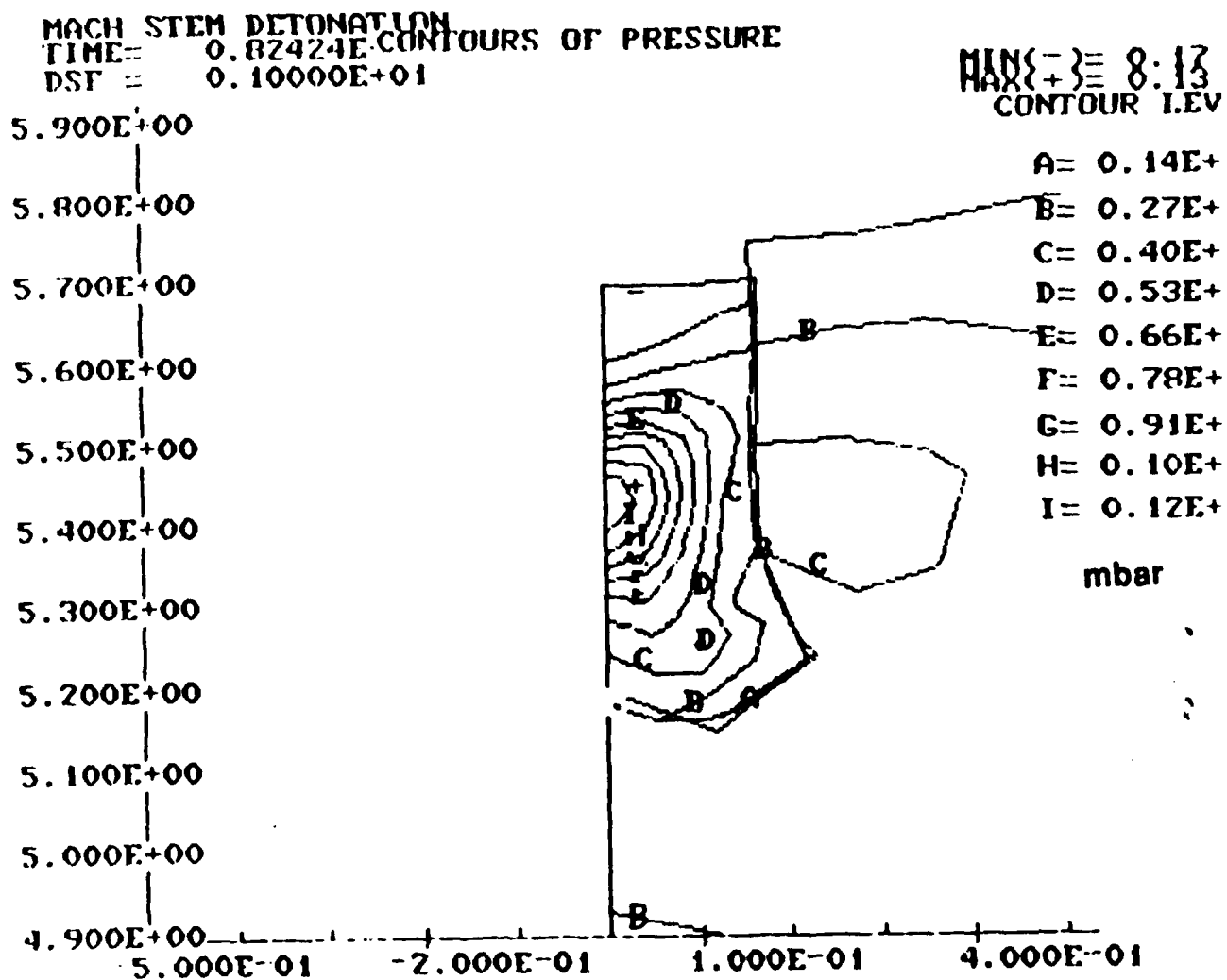
Figure 7. Pressure for a 0.18 cm copper rod in a Mach stem at 8.24 μs
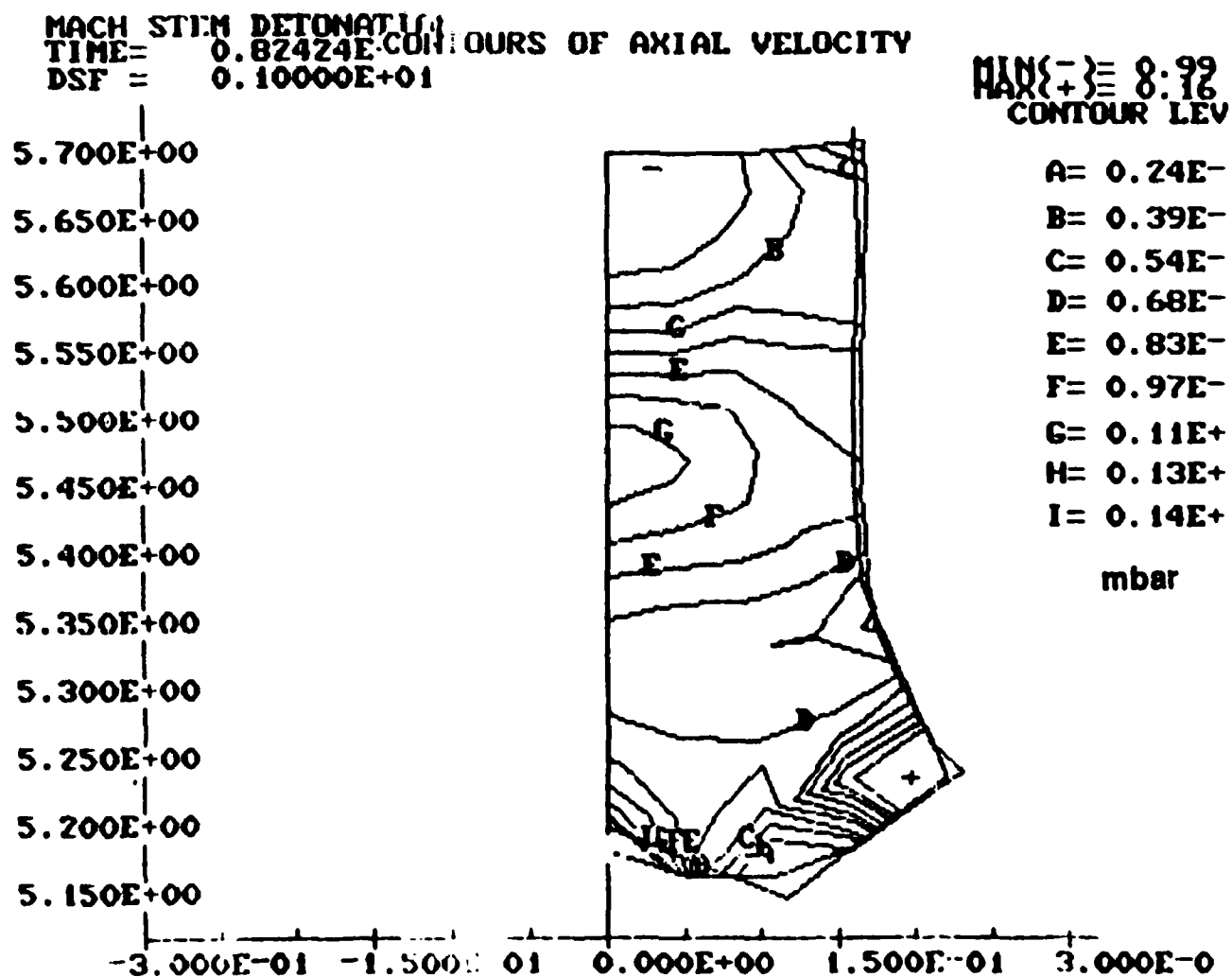
Figure 8. Axial Velocity for a 0.18 cm copper rod in a Mach stem

KEY

- ● Aluminum rod/Mach stem
- ▲ Aluminum rod/PBX9404
- ⊖ Long Aluminum rod/Mach stem
- ⊖ Copper rod/Mach stem
- △ Copper rod/PBX9404
- ★ Experimental .254cm thick plate/PBX9501
- ✳ Gurney value to match with experiment
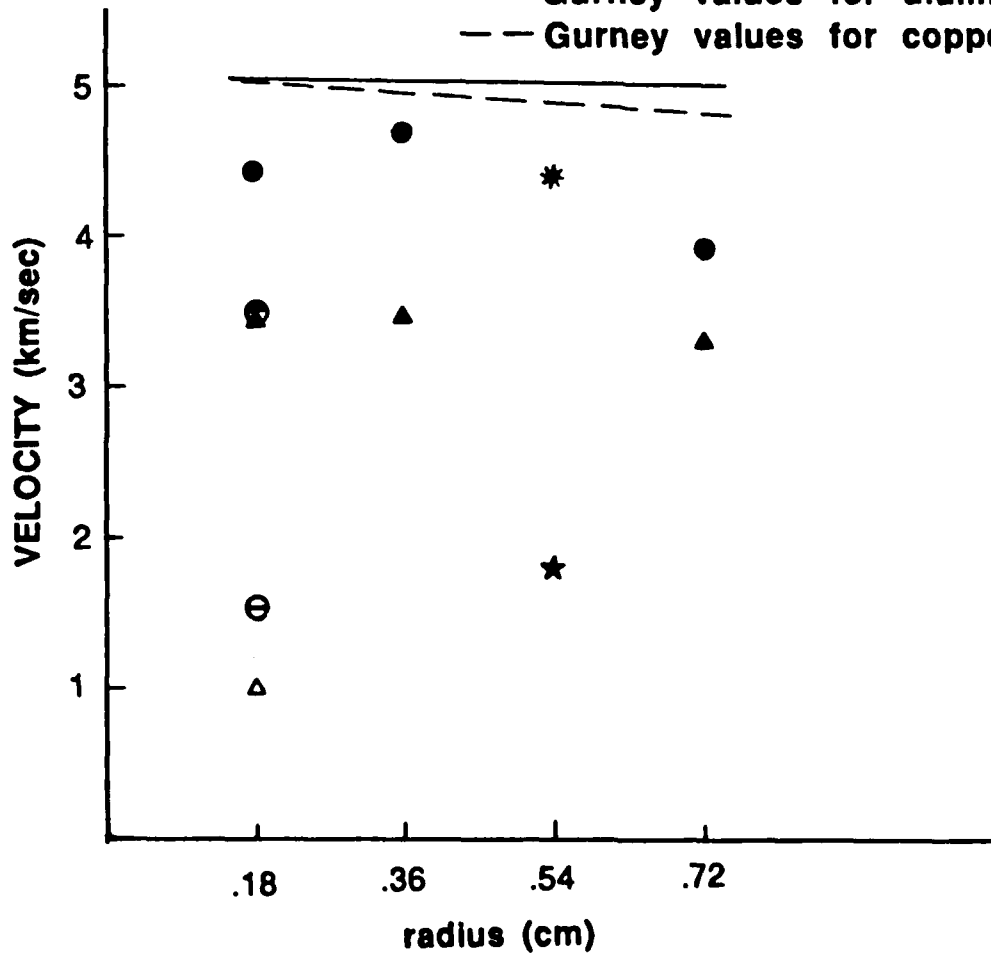- —— Gurney values for aluminum plates
- – – Gurney values for copper plates
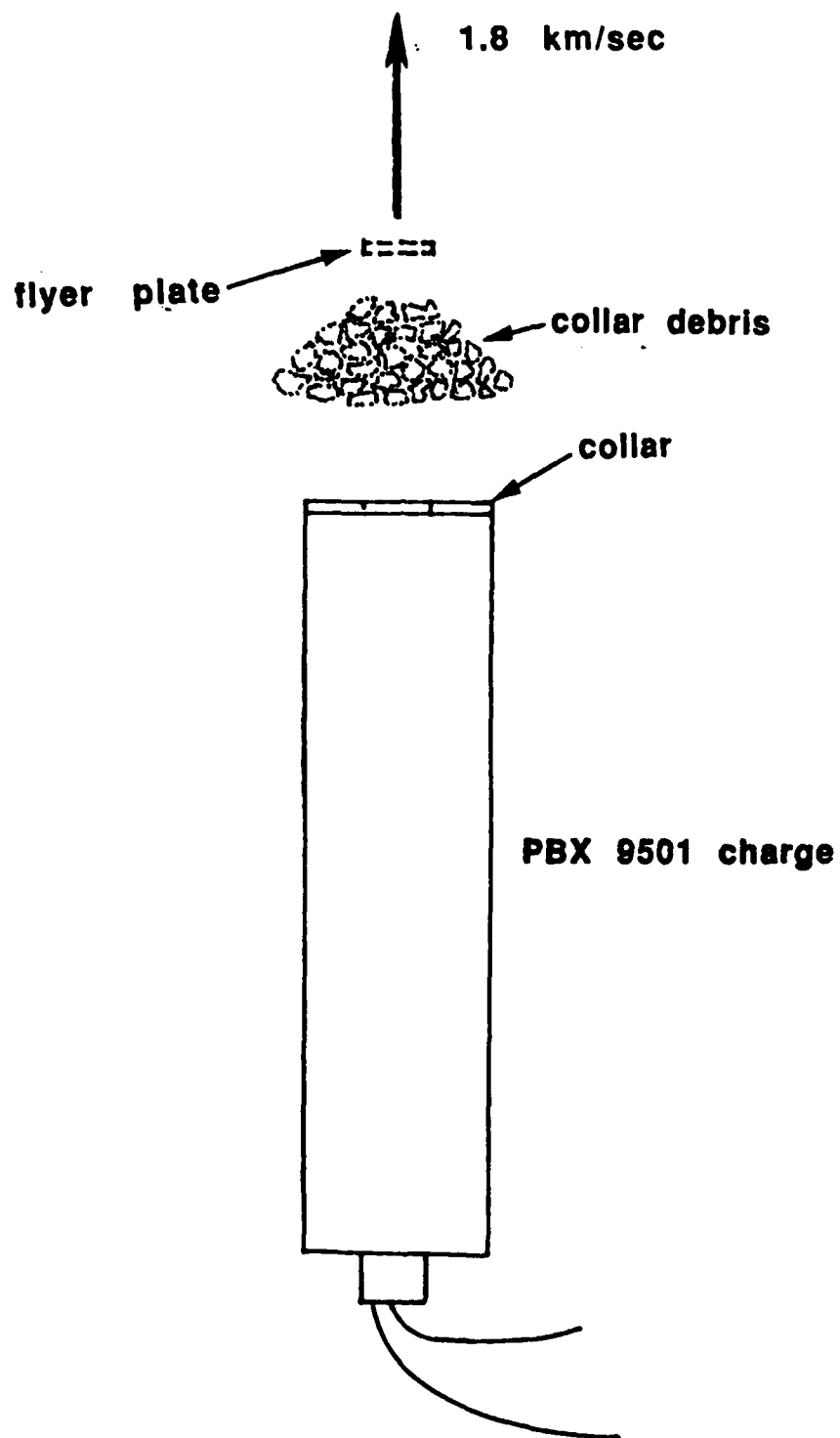
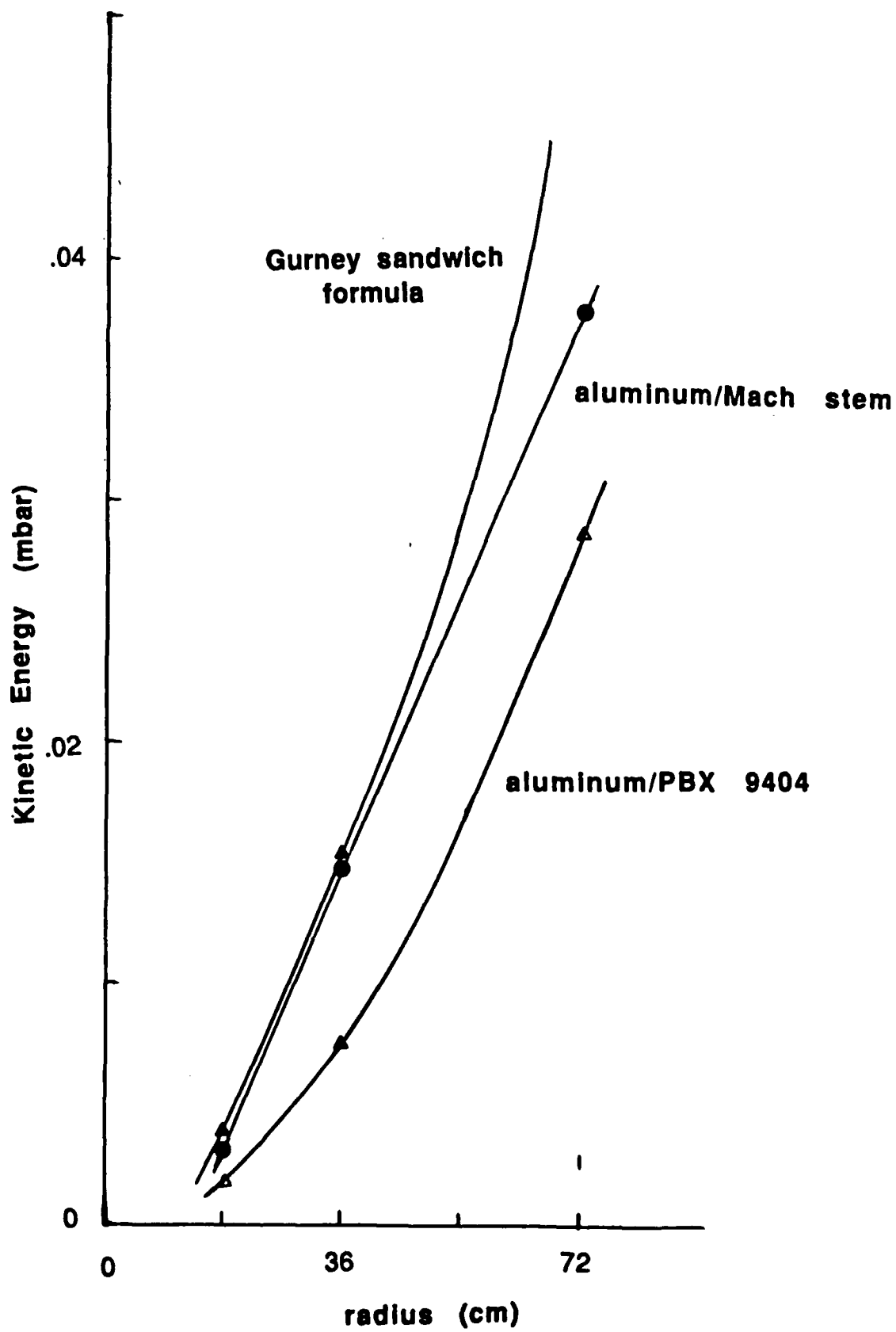Figure 9. Average axial velocity

1.8 km/sec

flyer plate

collar debris

collar

PBX 9501 charge

Figure 10. Copper flyer plate experiment

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Figure 11. Total kinetic energy of aluminum particles

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MACH STEM DETONATION
TIME=   0.11741E-CONTOURS OF AXIAL VELOCITY
DSF =   0.10000E+01

MIN(-)= 0.29
MAX(+)= 0.79
CONTOUR LEV

A= 0.34E+
B= 0.39E+
C= 0.44E+
D= 0.49E+
E= 0.54E+
F= 0.59E+
G= 0.64E+
H= 0.69E+
I= 0.74E+
cm/μsec
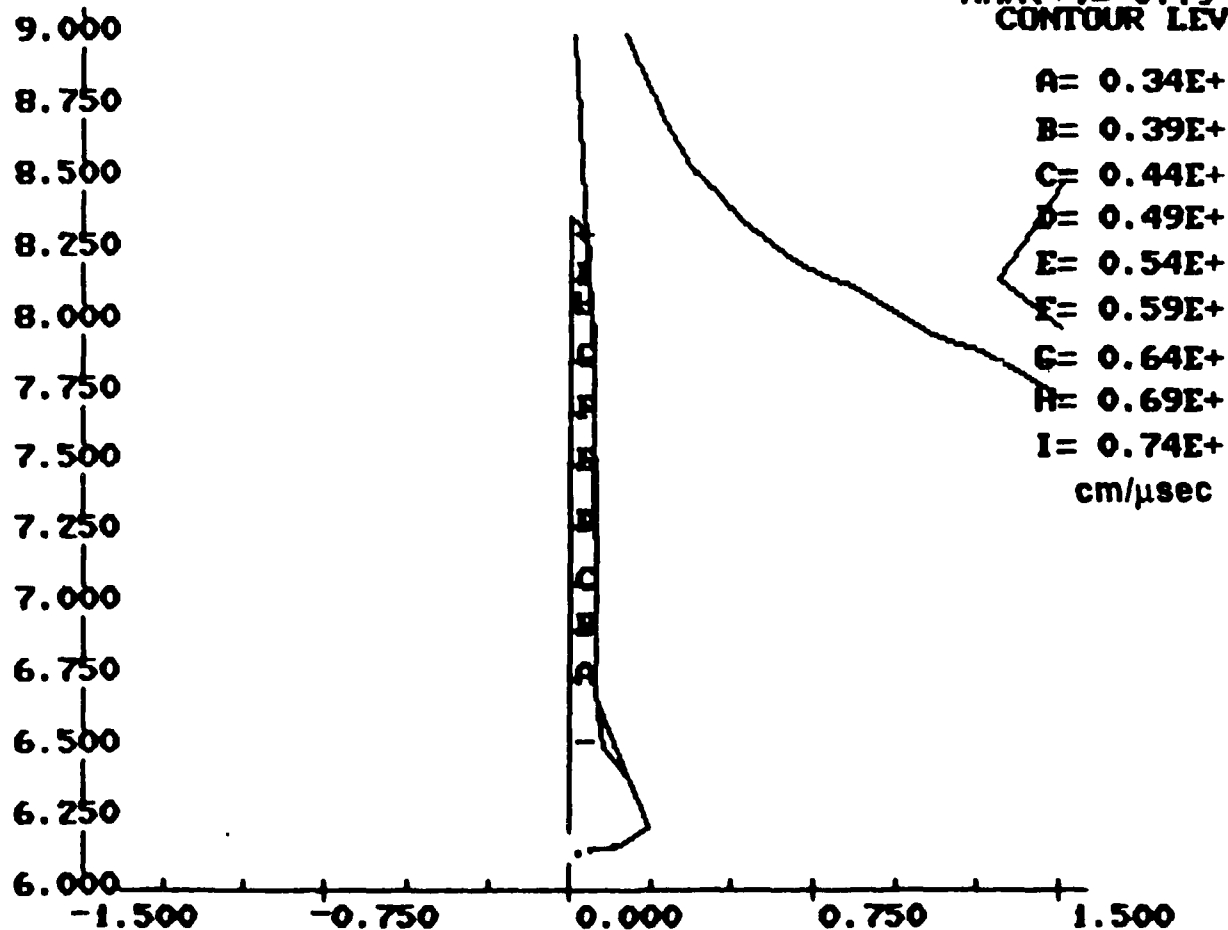
Figure 12. Axial velocity of aluminum rod launched by the Mach stem

CONTOUR LEV

A= 0.31E+
B= 0.34E+
C= 0.37E+
D= 0.40E+
E= 0.43E+
F= 0.46E+
G= 0.49E+
H= 0.52E+
I= 0.55E+

cm/μsec

```
9.000
8.750
8.500
8.250
8.000
7.750
7.500
7.250
7.000
6.750
6.500
6.250
6.000
     -1.500      -0.750      0.000      0.750      1.500
```
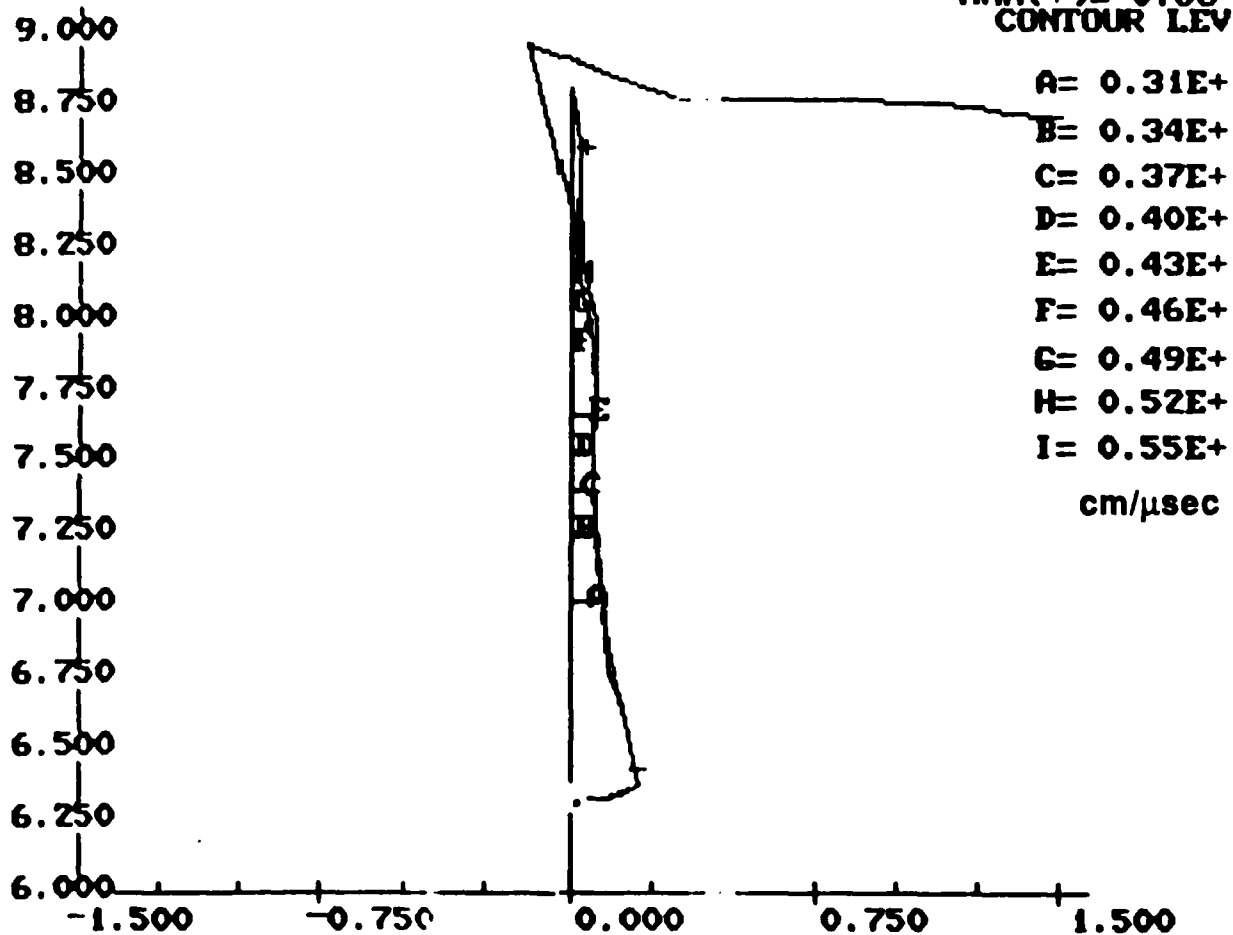
Figure 13. Axial velocity of aluminum rod launched by PBX 9404 alone
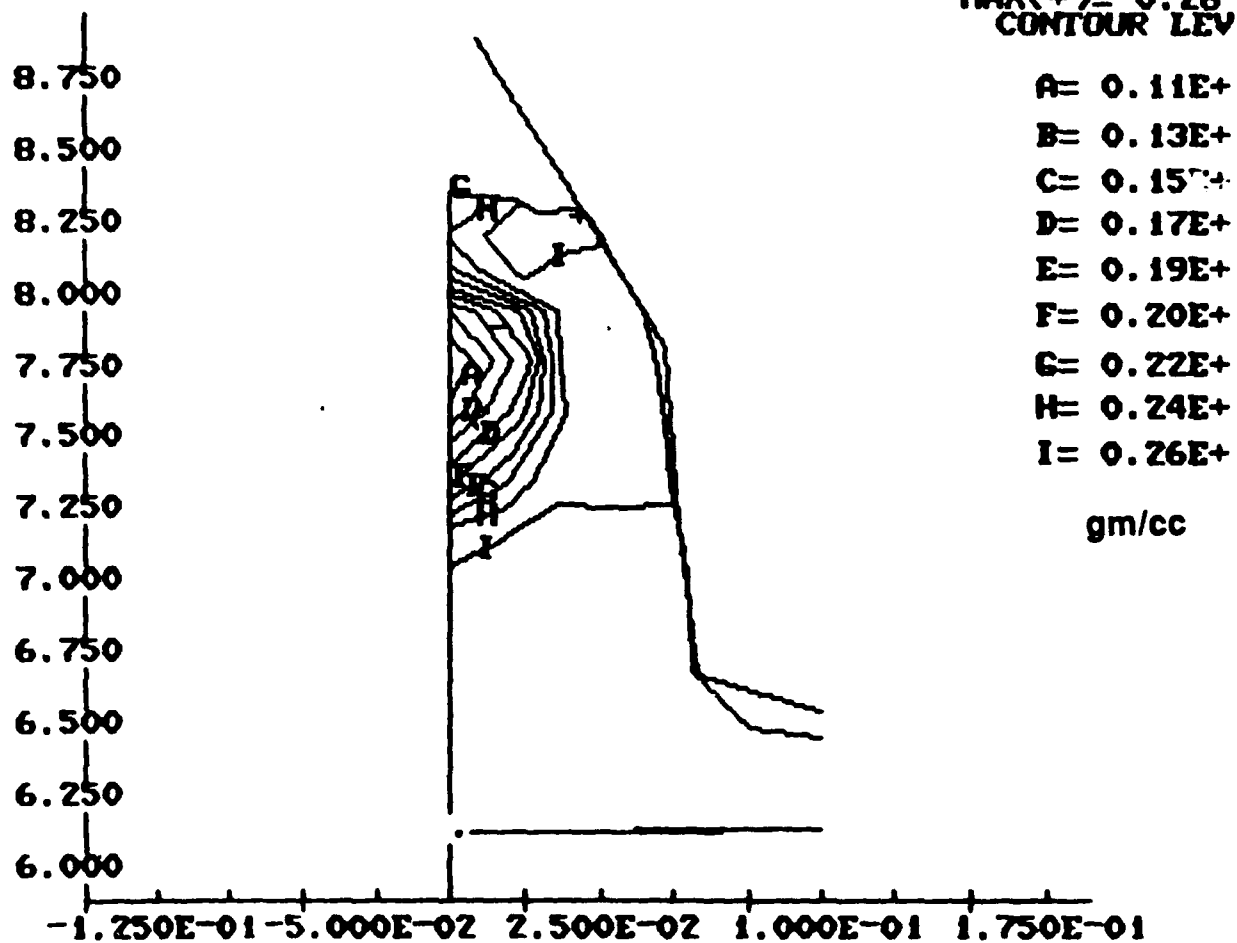
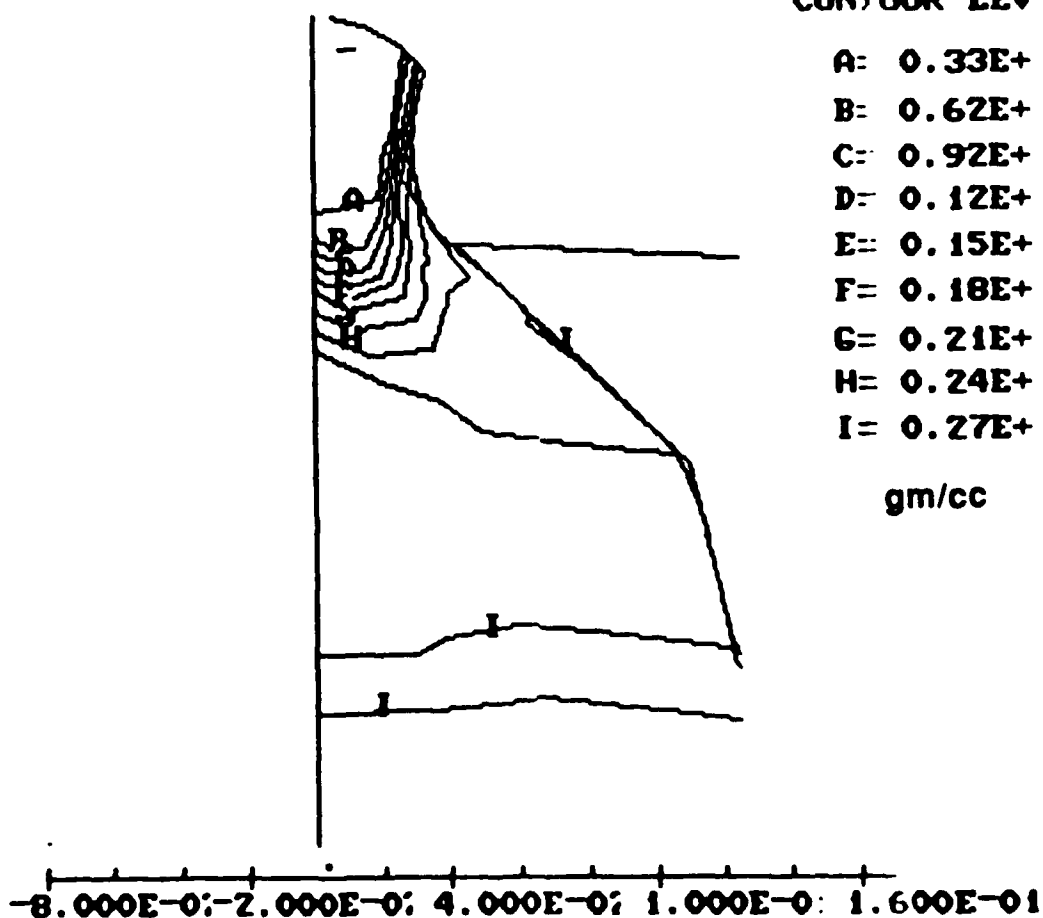Figure 14. Tip region density for aluminum rod launched by the Mach stem

Figure 15. Tip region density for aluminum rod launched by PBX 9404 alone

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2. Baker, E., Dalrymple, E., Fishburn, B., Fuchs, B., Howell, J., and Lu, P., "Axisymmetric Steady State Detonation Mach Stems and Semi-infinite Steel Whiteness Plate Interaction," Technical Report ARAED-TR-88008, U.S. Army Research, Development and Engineering Center, Picatinny Arsenal, NJ, July 1988.

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